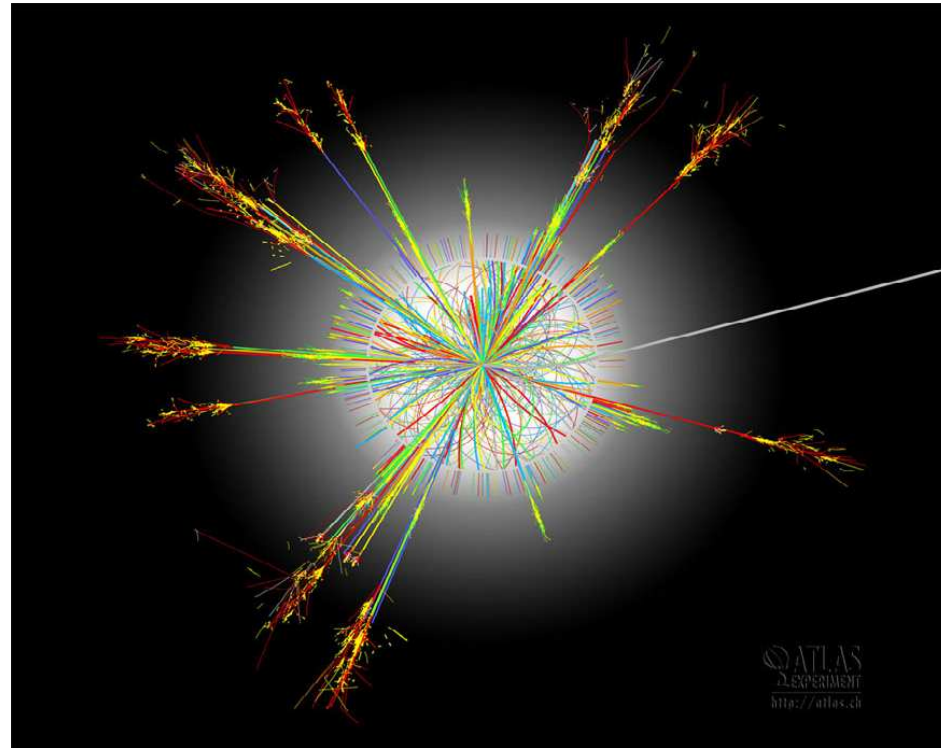


# An Overview of High Energy Physics



Cosmas Zachos, HEP



# *Simple sources and references*

The Particle Adventure, <http://particleadventure.org>

The Nobel Foundation,  
[http://nobelprize.org/nobel\\_prizes/physics/](http://nobelprize.org/nobel_prizes/physics/)

D Perkins, Intro. to High Energy Physics (Addison-Wesley)

D Griffiths, Intro. to Elementary Particles (Wiley-VCH)

RP Feynman, QED (Penguin)

PCW Davies, The Forces of Nature (Cambridge U Press)

F Close, Particle Physics: A Very Short Introduction  
(Oxford)

GF Giudice, A Zeptospace Odyssey (Oxford)



# *Particle Physics Booklet*

- <http://pdg.lbl.gov> Latest listings and properties of all known particles, searches (limits) for hypothetical ones, and nice reviews.
- One copy is available by request, for free, either:
  - On the web at <http://pdg.lbl.gov/pdgmail>
  - By email from [pdgrequest@lbl.gov](mailto:pdgrequest@lbl.gov)
  - By postal mail (!):

Particle Data Group, MS 50R6008  
Lawrence Berkeley National Lab  
One Cyclotron Road  
Berkeley, CA 94720-8166 USA



# *What is High Energy Physics?*

- High Energy physics explores objects that are **very energetic** and **very small**: the fundamental structures of **matter** and **energy** and the interplay between them.
- These are the **Elementary Particles** and their interactions — hence the alternative name, “**Particle Physics**”.
- Led to discovery of **new laws of Nature** with exquisite **mathematical beauty**.  
(Much of the relevant mathematics, some of it quite **older**, had been considered esoteric—until nature was recognized to **rely** on it, after all!)



# *Small and Energetic*

These tell us what theories we should use for our physics.

- “Small” means that **QUANTUM MECHANICS** is important, where particles tend to behave a bit like waves, according to de Broglie’s relation:

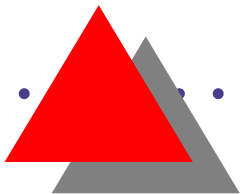
$$\text{wavelength} = \frac{h}{\text{momentum}} \quad \text{or} \quad \lambda = \frac{\hbar}{p}$$

$h \equiv 2\pi\hbar$  is Planck’s constant and small,  $6.63 \times 10^{-34}$  Js.

- “Energetic” means that **SPECIAL RELATIVITY** is important, and we should use Einstein’s

$$E = \sqrt{(mc^2)^2 + (pc)^2}$$

$c$  is the vacuum speed of light and large,  $3.0 \times 10^8$  m/s.





# *What do we mean?*

- In the Particle Physics Booklet one finds, for example:  
“... yields an average W-boson mass of 80.4 GeV ...”

Why is a mass being reported in units of energy?

$$[1 \text{ GeV} = 10^9 \text{ eV} = 1.6 \cdot 10^{-10} \text{ J}]$$

- Similarly, why is the “radius” of the proton often approximated by  $4 \text{ GeV}^{-1}$ ?

Why is a length represented by an inverse energy?



# Natural Units

The traditional set of units that we are most familiar with is  $\{M, L, T\}$ . In terms of these, the dimensions of our three important quantities in High Energy Physics are:

$$[c] = [\text{velocity}] = LT^{-1}$$

$$[\hbar] = [\text{length} \times \text{momentum}] = ML^2T^{-1}$$

$$[E] = [\text{mass} \times \text{velocity}^2] = ML^2T^{-2}$$

However, now we realize that we can invert these relationships so that the set  $\{M, L, T\} \longrightarrow \{[c], [\hbar], E\}$ :

$$L = [\hbar][c][E]^{-1}$$

$$M = [E][c]^{-2}$$

$$T = [\hbar][E]^{-1}$$



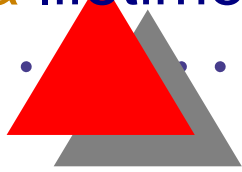

# Translation

For simplicity, we blind ourselves to  $\hbar$  and  $c$ , so we skip them (set  $\hbar = c = 1$ ), with the understanding that, since they have distinct dimensions, we can always reinstate them in formulae uniquely, using dimensional analysis. The new dimensions are:

$$\text{length} \sim L = [\hbar][c][E]^{-1} \rightarrow [E]^{-1}$$

$$\text{mass} \sim M = [E][c]^{-2} \rightarrow [E]$$

$$\text{lifetime} \sim T = [\hbar][E]^{-1} \rightarrow [E]^{-1}$$

- So a mass of 80.4 GeV really means 80.4 GeV/ $c^2$  and,
  - a proton radius of 4 GeV $^{-1}$  is really  $r = 4 (\hbar c) \text{ GeV}^{-1} = 4 \cdot (6.63 \cdot 10^{-34} \cdot 3 \cdot 10^8) / (2\pi \cdot 1.6 \cdot 10^{-10}) m = 8 \cdot 10^{-16} m$ .
  - a lifetime of 1/63 keV really means  $\sim 10^{-20} \text{ sec}$ .
- 





# High Energy Accelerators


How do you study the innards of a gadget —or a car— if you don't have the tools to pick it apart? You might smash it against a wall, or another car, and look at the ejecta: we learn about atoms and nuclei this way, by accelerating them, **colliding** them, and studying the fragments.

But, at **very high energies**, something different happens: ( $c = 1$ ) when you accelerate particles to large momenta

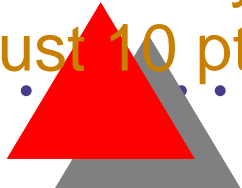
$p_{\text{large}}$  and energies  $E = \sqrt{m_{\text{small}}^2 + p_{\text{large}}^2} \gg m_{\text{small}}$ , you have enough energy to **produce new types of matter** to study: **unstable new particles**.

It is as if you collide cars to get bicycles, watermelons, shoes, iPods...



- 
- This is a crucial feature of High Energy Physics: the creation of new (unstable) forms of matter by consuming high energies.  
Sometimes the universe does this for us: cosmic rays.
  - Our neighbors at Fermilab accelerate protons and anti-protons in their Tevatron collider:

$$m_{\text{proton}} \approx 1 \text{ GeV}$$
$$E_{\text{total}} \approx 2 \text{ TeV} = 2000 \text{ GeV} \sim 3 \text{ ergs!}$$

- Physicists there produced (and discovered) the heaviest elementary particle yet found — the top quark of mass 175 GeV.
  - Today, the highest energy collider in the world is the Large Hadron Collider (LHC) in Geneva, Switzerland; ultimately, it will reach  $E_{\text{total}} = 14 \text{ TeV}$ : protons going just 10 pts per billion (7m/hr) slower than light ( $c$ ).
- 



# *Energy vs Sizes*

Most of the particles that we produce in a high energy collision are unstable—they do not live for very long.

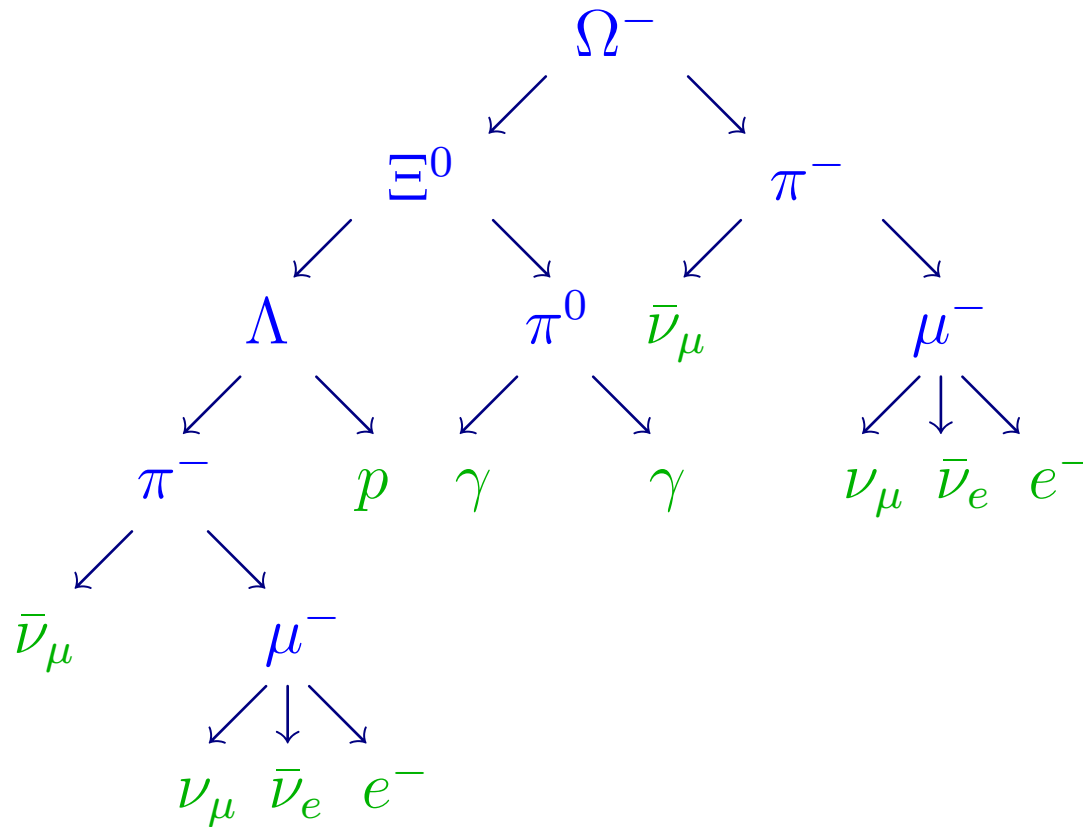
- The higher the mass that a particle has, the shorter it lives, so the shorter the distance it travels.
- For instance, the top quark is not seen directly, but is observed via its multi-stage decay:

$$\begin{aligned} \text{top quark } (t) &\longrightarrow W \text{ boson } (W^+) + \text{bottom quark } (b) \\ &\hookrightarrow \text{positron } (e^+) + \text{neutrino } (\nu_e) \end{aligned}$$

- Part of the challenge of experimental high energy physics is figuring out exactly where all the particles detected came from!
- 

# Multi-stage decay signatures: the $\Omega^-$

The particle known as the  $\Omega^-$  was an early successful prediction of the theory, and was discovered in the 60s:





# *The Electromagnetic Spectrum*

$$E = \frac{hc}{\lambda} \implies \text{high energy} \sim \text{short wavelength}$$

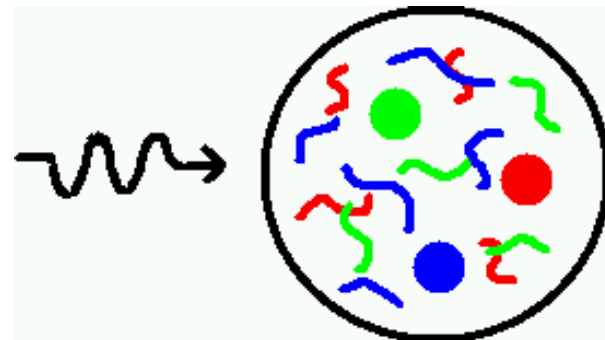
Region	Wavelength (m)	Energy (eV)
Radio/TV	$> 0.1$	$< 10^{-5}$
Radar/Microwave	$0.1 - 10^{-4}$	$10^{-5} - 0.01$
Infrared	$10^{-4} - 7 \cdot 10^{-7}$	$0.01 - 2$
Visible	$7 \cdot 10^{-7} - 4 \cdot 10^{-7}$	$2 - 3$
Ultraviolet	$4 \cdot 10^{-7} - 10^{-9}$	$3 - 10^3$
X-Rays	$10^{-9} - 10^{-11}$	$10^3 - 10^5$
Gamma Rays	$< 10^{-11}$	$> 10^5$
Tevatron	$10^{-19}$	$2 \cdot 10^{12}$
LHC	$2 \cdot 10^{-20}$	$10^{13}$

# The Uncertainty Principle in Particle Probes

To **resolve** an object, we can “look in it” with particles which have a wavelength **less** than the object’s size.

- Size of an atom  $\sim 0.2 \text{ nm} = 2 \cdot 10^{-10} \text{ m}$ .  
     $\hookrightarrow$  X-Ray diffraction
- Size of the nucleus of Uranium-238  $\sim 10^{-14} \text{ m}$ .  
     $\hookrightarrow$  Nuclear physics
- Size of the proton  $\sim 10^{-15} \text{ m}$  (=a fermi).  
     $\hookrightarrow$  High-energy physics

↓  
nuclear sub-structure  
↓  
quarks



- Size of a quark  $\sim ??$



# Particle Properties

Just as with atoms, it is possible to classify the elementary particles that we know about into families with similar properties.

- Which particles among these are ‘truly’ elementary?

Stable:  $p, n, e^{\pm}, \gamma, \nu$

Unstable:  $W^{\pm}, t, \Omega^{-}, \Xi^0, \Lambda, \pi$

- What characteristics do they share?
  - Mass?
  - Electric charge?
  - Something else we don't know about?

# The “Periodic Table” of HEP

	Matter (fermions)				Radiation			
	leptons		quarks		bosons			
charge	-1	0	+2/3	-1/3	0	0	$\pm 1$	0
interactions ↓	$e^-$	$\nu_e$	$u$	$d$	$g$ $\gamma$ $W^\pm$ $Z^0$			
	$\mu^-$	$\nu_\mu$	$c$	$s$				
	$\tau^-$	$\nu_\tau$	$t$	$b$				
strong			X	X	★			
electromagnetic	X		X	X	★			
—weak	X	X	X	X	★   ★			
gravitational	X	X	X	X	X	X	X	X

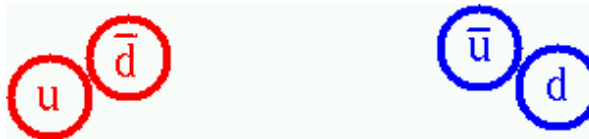
... plus the fermions' anti-particles, with opposite charge.



# Hadrons and confinement

- We don't see quarks and gluons directly, because the strong 'color' interaction confines them into hadrons.

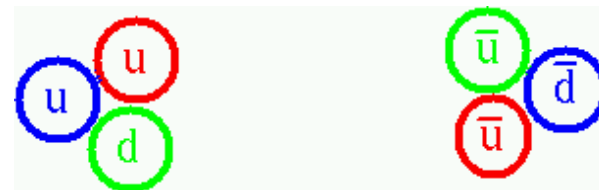
mesons -  $(q\bar{q})$



e.g. pion,  $\pi^+$ ,  $u\bar{d}$  (charge =  $+2/3 + 1/3 = +1$ )

kaon,  $K^0$ ,  $d\bar{s}$  (charge =  $-1/3 + 1/3 = 0$ )

baryons -  $(qqq)$  or  $(\bar{q}\bar{q}\bar{q})$



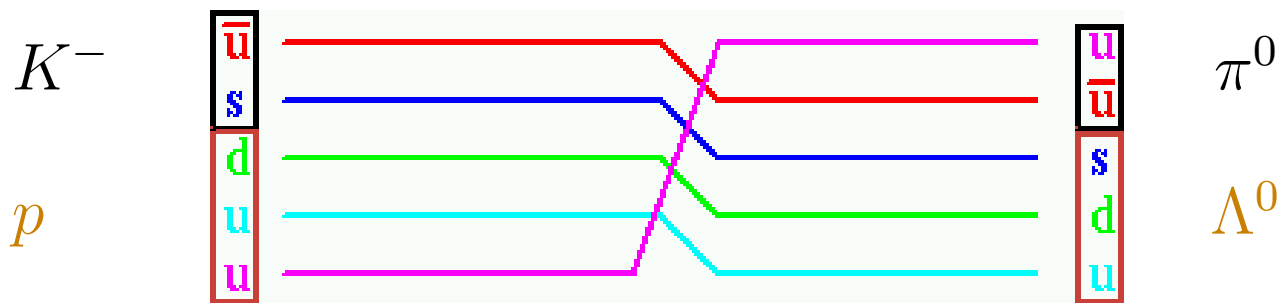
e.g. proton,  $uud$  (charge =  $2/3 + 2/3 - 1/3 = +1$ )

neutron,  $udd$  (charge =  $2/3 - 1/3 - 1/3 = 0$ )

# Conservation Laws

- By writing out the quark content of baryons and mesons it is easy to decide what types of reactions are allowed.
- We are used to the conservation of electric charge and must augment this with a few more laws – such as conservation of “strangeness” under the strong force.

e.g.  $K^- (\bar{u}s) + p (uud) \longrightarrow \Lambda^0 (uds) + \pi^0 (u\bar{u})$





# Forces of Nature

Let's compare the forces at energies (and distances) typical for HEP, say  $E \sim 1 \text{ GeV}$  ( $r \sim 0.1 \text{ fm}$ ).

	strong	e.-m.	weak	gravity
strength	1	$\alpha = \frac{1}{137} \sim 10^{-2}$	$10^{-7}$	$10^{-38}$
lifetime(s)	$10^{-23}$	$10^{-16}$	$10^{-8}$	—
boson	gluons	photon	$W^{\pm}, Z$	gravitons
theory	QCD	QED		Quantum
symmetry	$SU(3)_{\text{color}}$	$U(1) \times SU(2)$		Gravity

QED = Quantum Electrodynamics

QCD = Quantum Chromodynamics

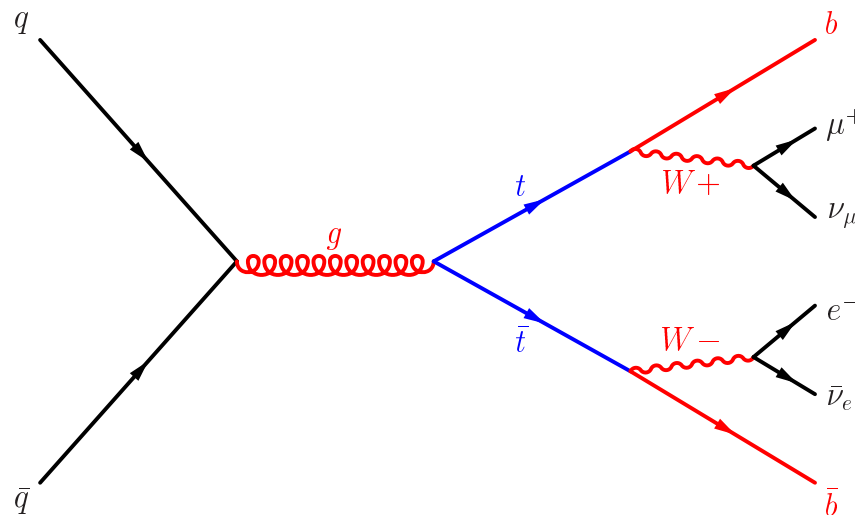
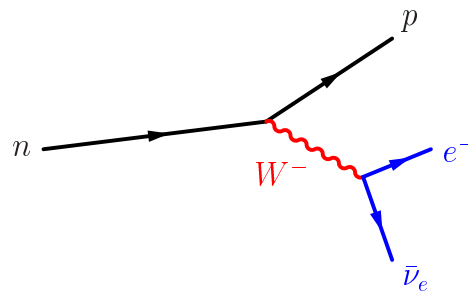
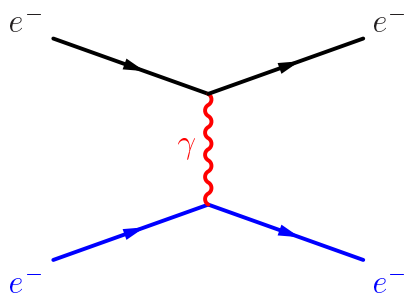


# *Quantum Field Theory*

- Particles interact with each other through fields. Classically, we are familiar with electric-magnetic and gravitational fields.
- In HEP, quantum mechanics is important, with the result that these fields are quantized. The particles interact by exchanging field quanta.
- These quanta are the bosons that we have been talking about —  $g$ ,  $\gamma$ ,  $W^\pm$  and  $Z$ .
- We describe the interactions of these particles by a Quantum Field Theory—The book of nature is written in math.
- Still, Quantum Field Theory has a practical representation that we often use: Feynman diagrams.

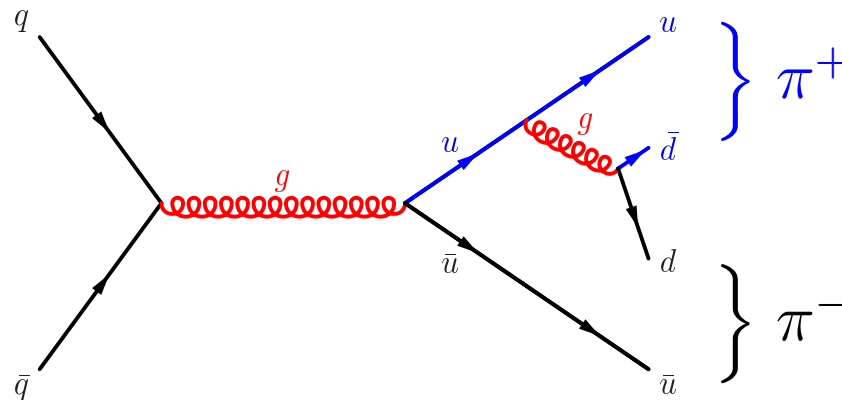
# Feynman Diagrams

- Simple, intuitive pictures ...
- ... to represent all that complicated math.



# Jets

- How do hadrons form after a violent collision? Somehow, all the quarks and gluons rearrange themselves to become hadrons.
- The result is **jets** of hadrons that look very much like the paths of individual quarks.



# Renormalization

According to the uncertainty principle, the vacuum may fluctuate, which causes all the field strengths and interactions to be renormalized.

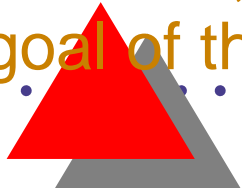


This causes the strong interactions to become weaker at higher energies, called **asymptotic freedom**. This is the flip-side of **confinement**, where the interactions become stronger at lower energies (longer distances).



# *The Higgs Boson*

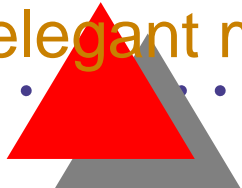
The **Higgs Boson** is like a ‘missing link’ in our “periodic table”, the **Standard Model**, in which electromagnetism and the weak interactions blend together.

- Have **Not** found the Higgs (“so far” ?).
  - Without the ‘Higgs mechanism’, the theory would not predict that the **W-boson** and **Z-boson** have **masses**, and big ones, at that. The mechanism through which the “cousins” of the Higgs make these bosons massive is called mass generation through **Spontaneous Symmetry Breaking**.
  - This mechanism must operate one way or another: with a “conventional” Higgs, or subtler multiple Higgs particles, or something else... We wish to know! The goal of the LHC: the **physics of zeptospace**.
- 





# *Gravity, Super-Theories, Speculative Visions*

- Just as we realized that we could describe the weak and electro-magnetic theories within one embracing electroweak theory, attempts have also been made to unify this theory with that of the strong interactions, into **Grand Unified Theories**.
  - Other theorists try to link fermions and bosons through **supersymmetry**, introducing yet more undiscovered particles (e.g. **squarks**, partners of the regular quarks). These theories naturally incorporate gravity, leading to even more unification — **supergravity**.
  - Ultimately, these theories may be embedded in a speculative framework, **superstrings, brane-world theories**, etc, in more than 4 dimensions... inside elegant mathematical worlds, prettier than ours!
- 

# *ATLAS detector at the CERN LHC*

